Appendix B (26 pg

EVALUATING THE ENVIRONMENTAL PERFORMANCE OF PASSENGER VEHICLES

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Abstract

Intention, Goal, and Scope. This paper proposes a metric that reflects the environmental and resource impacts of passenger vehicles. Primarily intended to assist consumers in purchasing decisions, the metric is designed to provide timely, relevant and meaningful information that captures most of the impacts occurring in the vehicle life cycle.

Background. Vehicles are significant emitters of air pollutants and a major influence on the environment. A need exists for comprehensive, objective and comparative information to describe these impacts. Reporting of environmental performance on a brand/model basis can increase consumer awareness and enhance vehicle manufacturer's marketing practices.

Methods. Using principles of life cycle assessment (LCA), objective criteria for vehicles are proposed that use available or reasonably obtainable and quality-assured data. Previous LCA studies are reviewed to help formulate the suggested metric, which is comprised of components that represent energy efficiency and greenhouse gas emissions of carbon dioxide (CO_2) and other gases (40% weight of the total score), emissions of ozone-forming pollutants nitrogen oxides and non-methane hydrocarbons (25%), emissions of toxicants carbon monoxide (12.5%) and particulate matter (12.5%), and solid waste generation and resource consumption (10%). Scores for advanced technology vehicles are derived in a manner consistent with conventional gasoline and diesel-powered vehicles. The weighting of the

components is based on LCA results and the severity of impacts. The energy efficiency and pollutant scores, which are proportional to the reduction in emissions from a baseline vehicle, are based on emission certifications, highway and city fuel economy estimates. The waste generation and resource consumption score is based on the percent recycled content in the vehicle. At present, the recycled content of vehicles is not available on a brand/model basis, however, this information is not difficult to determine.

Results. The metric emphasizes environmental burdens in the use stage, which LCA studies indicate account for majority of emissions in the vehicle life cycle. The 200 brand/models and 1,450 engine/drive train configurations in the available 2000 model year demonstrate a large range of emissions, e.g., greenhouse gas emissions range from 176 to 1187 g/mile in CO_2 equivalents. The analysis demonstrates trade-offs between vehicle efficiency and emission standards that can be used by a consumer or manufacturer to achieve a desired environmental performance target.

Conclusions. While subject to limitations arising largely from information gaps, the suggested metric provides a consistent and comprehensive indicator of environmental performance useful in comparing the environmental performance of vehicles and guiding purchasing decisions.

Future Prospects. No single metric can capture the diversity of all possible impacts, concerns and trade-offs resulting from vehicles or other complex systems. Because the weighting of the component measures is judgmental and based on incomplete information, results are considered as a first step in a comparative rating system, and the need to update the metric as additional information becomes available is emphasized. Nevertheless, the suggested metric is believed to provide a useful and objective indicator of the life cycle impact of vehicles.

Keywords

Air pollutants; automobiles; emissions; environmental indicators; green labeling, greenhouse gas; indicators; life cycle assessment; motor vehicles; pollution; recycling; vehicles;

Introduction

Transportation in general and passenger vehicles (automobiles, sport utility vehicles, and light and medium duty vehicles) in particular are significant emitters of air pollutants and a major influence on the environment. Of the six criteria pollutants regulated by the US Environmental Protection Agency, transportation sources emit 60% of carbon monoxide (CO) emissions nationwide and 95% of the CO in cities, 21% of air toxics (including non-methane hydrocarbons or NMHCs) nationwide and the predominant fraction in urban areas, nearly half of the nitrogen oxides (NO_x) nationwide, and almost a third of particulate matter (PM).[1,2] Both NMHCs and NO_x are precursors of ozone (O_3), the most widespread urban air pollutant. Globally, transportation accounts for about 25% of greenhouse gas (GHG) emissions including carbon dioxide (CO_2), and a higher percentage in the US. Due to sharp increases in the demand for transport and comfort, CO_2 emissions in the transport sector worldwide may increase dramatically, e.g., by 200% in 2025.[3] By any measure, the environmental impacts of vehicles are substantial and growing.

Information regarding the environmental impacts of vehicles that can be used to guide consumer purchases may be obtained from product rating schemes (ecolabels),[4-8] eco-efficiency indicators,[9] corporate reports,[10,11] and elsewhere. However, evaluating environmental and natural resource impacts in a comprehensive, objective and comparative manner remains challenging for several reasons. First, environmental and resource impacts are very diverse. Pollutant emissions occur to air, water and land, and each pollutant has different consequences. Air emissions of NMOCs and NO_x may be toxic themselves and together form other pollutants, e.g., O_3, while emissions of CO_2, methane (CH_4) and nitrous oxide (N_20) contribute to global warming and climate change. Second, impacts occur throughout the product life cycle, i.e., in the production, use and disposal phases, and not all impacts can be readily and accurately evaluated. Third, the derivation of a metric to consolidate and communicate environmental performance is subjective and potentially controversial. Measures such as the total tonnage of air emissions do not reflect the environmental significance of the different air pollutants. Fourth, the source of the information may influence its objectivity, content and relevance.[10] Despite these and other arguments regarding their effectiveness and credibility,[6] interest by industry, government and consumers in environmental performance measures remains high.

This paper proposes a metric to evaluate impacts of vehicles on human health, the environment and natural resources. Using principles of life cycle assessment (LCA), criteria are proposed that capture the major share of environmental impacts and that use available or reasonably obtainable and quality-assured data. The metric can assist consumers in their purchasing decisions, as well as indicate desirable vehicle

to vehicle manufacturers. After summarizing key features of the approach, the recommended environmental criteria and metric are described. The paper concludes with limitations of the approach and recommendations for future work.

Approach

The overall goals for the metric, taken in part from those used to define eco-indicators,[9] are to provide relevant and meaningful information related to the protection of health and the environment; to be clearly definable, measurable, transparent and verifiable; and to be understandable and meaningful to stakeholders, specifically vehicle purchasers. The metric attempts to capture most of the environmental impacts attributable to passenger vehicles, including pollutant emissions, energy consumption, solid waste generation, and resource consumption.

LCA concepts guide the formulation of the metric. There is growing experience with LCAs for vehicles using both material flow (engineering)[12-17] and input-output (econometric) analyses.[18,19] A number of studies have been performed for components of vehicles (batteries, manifolds, etc.), as well as the transportation fuel cycle.[20-22] These studies show that the principal environmental burdens associated with vehicles include emissions to air, water and land (as solid waste), and the primary resources consumed are energy, raw materials, and water. Burdens are distributed between vehicle manufacturers, material and component suppliers, petroleum extraction, refining and distribution, and others. The LCA studies provide a comprehensive examination of environmental burdens.

It is recognized that no single metric is likely to capture all impacts and other values implied by notions of sustainability. Indeed, a recent working group suggested the use of 40 separate indicators to track a range of issues.[23] More fundamentally, LCA or other tools may be unable to provide reasonable estimates of certain environmental impacts due to simplifying assumptions, e.g., the lack of spatial and temporal emission information, and the use of linear, no threshold dose-response or damage functions.[24-26] Aspects of LCA tools and models are complex, and single indicator approaches have not been critically reviewed.[27] Both site-specific and generic information, e.g., toxicity equivalencies, may be incomplete, inappropriate, and out-of-date.[28] Allocations of burdens for processes that contribute to more than one product system remain problematic.[29] The various valuation procedures[30] can provide different rankings.[31] Even the most thorough life cycle inventories have gaps, e.g., the vehicle manufacturing component is limited due to the incompleteness of plant data, and environmental burdens are probably underestimated.[32,33] Emissions during vehicle use may be underestimated due to deterioration and failures of emission control systems and limitations of emission testing procedures,[34]

and different emission estimation methods can yield disparate results.[35] Emissions also depend on "external" factors such as fuel volatility and sulfur content, ambient temperature, traffic and driving cycles, and the presence and nature of vehicle inspection and maintenance ("smog check") programs. For such reasons, most LCAs emphasize inventories, environmental burdens that are classified and characterized into a few metrics, and environmental burdens are treated with the simple notion that "less is better."

Despite their limitations, LCA analyses can provide a sufficient basis for comparison within an impact category, although alternative assessment tools and criteria may be needed in some cases.[25] In addition, the comprehensive life cycle inventories completed for vehicles [12-19] have provided largely comparable results regarding the identification and quantification of the significant emission sources, despite substantial differences in methodologies and assumptions, e.g., vehicle type, weight, drive train, and driving cycle. Finally, the reliability and technical integrity of results will be enhanced by guidelines, requirements and peer review steps being developed by ISO, EPA, SETAC and others.[36-40] Thus, the approach presented below is expected to evolve as new and enhanced information and procedures become available.

Air emissions

Air emissions related to vehicles include GHGs (CO_2, CH_4, N_2O), criteria air pollutants (PM, CO, NMHC, NO_x, sulfur dioxide [SO_2], and lead [Pb]), and hazardous air pollutants (e.g., benzene, formaldehyde). The apportionment of vehicle-related emissions to the major phases of the vehicle life cycle is shown in Fig. 1, based on the average fraction in three recent studies[15-17] that analyzed emissions from small, intermediate and large cars, all with internal combustion (IC) gasoline engines. For CO_2, the average of two IC powered vehicles and one electric vehicle (EV) is shown. The vehicle use phase (including fuel production) accounts for most GHG emissions (79 – 87% of CO_2, and 60 – 68% of CH_4), and most of the criteria pollutants (89 – 94% of CO, 81 – 90% of NO_x, 84 – 91% of NMHCs, and 63 – 70% of SO_x). Similarly, the most comprehensive review of the transportation fuel cycle shows the dominance of the use stage for CO, NMHC, NO_x, CO_2 and N_2O.[22] An input-output analysis of a midsize sedan also shows the dominance of the use stage for energy consumption and CO_2, as well as for emissions of the criteria pollutants (CO, NO_x, SO_x, PM_{10}).[19] Only one estimate of PM and Pb emissions is available (for a gasoline engine-powered sedan[16]) and the use phase accounts for 31% of PM (the percentage will be higher for diesel vehicles) and 1% of Pb emissions. Since the phase-out of Pb in gasoline, essentially the entire US has achieved the ambient standard for Pb.

In summary, the use phase accounts for the bulk of GHG emissions and emissions of most criteria pollutants. As discussed later, this is today's picture. In the future, expected reductions in vehicle emissions may increase the relative importance of emissions in other phases, e.g., manufacturing.

The relative ranking or weighting of emissions can be based on many factors, e.g., potency or toxicity of the chemicals, individual or population risks, population affected, marginal control cost, social cost, etc. GHG emissions might be prioritized given the magnitude and consequence of potential impacts, but uncertainties are very high. For conventional pollutants, photochemical and urban toxic pollution caused by NO_x and NMHC is widespread, and from 48 to 102 million people in the US are estimated to live in O_3 nonattainment areas (where the ambient standard is exceeded).[1] CO remains a serious problem, and ~9 million people live in CO nonattainment areas.[1] PM is potentially of great significance, however, nonattainment status and health impacts under the proposed PM ambient standard, which is based on particles below 2.5 μm dia ($PM_{2.5}$), are uncertain due to a lack of monitoring and other reasons.

Because they represent known problems affecting sizable populations and are currently regulated, the four conventional pollutants form half of the weight of the suggested measure, and each is weighted equally, i.e., 12.5%. GHG emissions, which potentially affect everyone, are given 40% of the score. This weighting is population-based, and roughly reflects the numbers affected by GHG emissions (40%), photochemical pollution (25% for NO_x and NMHC together), and toxicants (12.5% each for CO and PM). The remaining 10% is given to solid waste generation and resource consumption of the vehicle. This weighting is simple and likely to result in rankings that are comparable to that derived using other approaches. This weighting – as any other necessarily used in a scalar performance measure – is judgmental and based on the available but incomplete information. For these and other reasons discussed below, the weights are considered a first step, and the metric may evolve to become more comprehensive, reliable and impact-based (rather than burden-based).

The pollution prevention and energy conservation components in the metric are based on environmental burdens associated with air pollution emissions in the vehicle's use phase, including fuel production. The US DOE/EPA vehicle fuel economy is utilized for the energy conservation/GHG score, and US EPA[41] and State of California[42] vehicle emission certification standards for CO, NO_x, NMHCs and PM are used for the pollution prevention score. Certification standards provide a high degree of standardization and quality assurance, a critical need. Depending on the certification, allowable emissions are specified for vehicle ages from 50,000 to 150,000 miles. The 50,000-mile standard is used because it is common to all certifications, and it may reflect average emissions. Cars, light and medium duty

vehicles up to 8,500 lbs in weight (corresponding to vehicle types light duty trucks [LDT4] and medium duty vehicles [MDV3]) that are typically used as passenger vehicles are considered.

Energy efficiency and GHG emissions

As shown in Fig. 1, GHG emissions are dominated by the use phase. Over its lifetime, a typical vehicle will emit ~64,000 kg of CO_2 and ~50 kg of CH_4. The DOE/EPA Fuel Economy Guide's estimate of miles per gallon (mpg) serves as a proxy for GHG emissions. Vehicle fuel efficiency estimates (in mpg) are inversely proportional to GHG emissions from fuel production and vehicle use. Wang's transportation fuel-cycle model GREET 1.5[22] provides estimates of GHG emissions in CO_2 equivalents (including CO_2, CH_4 and N_2O) from feedstock, refining, distributing and vehicle operations.

To rank vehicles, the lowest mileage among passenger vehicles scores 0 points; the highest scores 40 points (Fig. 2). To reflect typical driving patterns, the average fuel economy for a vehicle is determined using DOE/EPA urban and rural mileage estimates, weights of 55 and 45%, respectively, to reflect driving patterns, and a harmonic average. The score is proportional to the reduction in GHG emissions and scaled to the range of the current model year (2000) average fuel economies, which range from 9.7 to 64.7 mpg (equivalent to to GHG emissions from 1187 to 176 g/mile). Fig. 2 shows diminishing returns, e.g., scores increase rapidly as low mileage vehicles are made more efficient, but point differences are small among efficient vehicles.

While this component of the environmental performance measure is designed to reflect energy efficiency and GHG emissions, high scoring vehicles are likely to be light in weight. Thus, high scoring vehicles are likely to utilize fewer resources and incur lower environmental impacts in their production and end-of-use phases.

Ozone forming pollutants – NO_x and NMHC

NO_x and NMHC emissions form the basis of the second component of the environmental performance measure. These pollutants form O_3, a widespread and significant pollutant, and NMHC emissions also contribute to urban toxic pollution. Emissions of NO_x and NMHC occur primarily during the vehicle use phase (Fig. 1).

All new vehicles must meet, at a minimum, Tier 1 emission levels. For cars, NO_x emission rates for Tier 1 and transitional low-emission vehicles (TLEV) are equivalent (0.4 g/mile). Current certification standards include several intermediate certifications: low-emitting vehicles and ultra-low-emitting vehicles (LEV = ULEV = 0.2 g/mile), level II LEV (LEV II = 0.05 g/mile), and super-ultra-LEV (SULEV

= 0.02 g/mile). Federal and California standards allow higher emissions for light duty trucks >3750 lbs (LDT2 and LDT3 Tier 1 = CA MDV2 = 0.7 g/mile, and for trucks >5750 lbs (LDT4 = CA MDV3 = 1.1 g/mile). California also specifies LEV, ULEV and SULEV emission standards for 5 weight classes of medium duty vehicles. For the NO_x component measure, the highest emitting vehicle obtains a score of 0; a zero-emission-vehicle (ZEV) without NO_x emissions in the fuel cycle receives 12.5 points. The score is proportional to the emission reduction from the NO_x floor (Fig. 3). Like the GHG emission score, the floor represents the highest emission rate among current passenger vehicles, namely, the federal and California emission standards for vehicles <8,500 lbs (LDT4/MDV3 classes).

NMHC emissions occur as refueling losses (now controlled by onboard refueling vapor recovery systems), starting emissions, evaporative and running losses (controlled by regulations on hot soaks, diurnal emissions, running losses), and tailpipe emissions. All vehicles must meet certification standards for these emissions. Current standards use the same running losses (0.05 g/mile) and refueling losses (0.2 g/gal) for all vehicles considered here.

Evaporative emissions of NMHC depend on vehicle design, climate, driving patterns, fuel vapor pressure, and other factors. A simplified approach is used to estimate NMHC emissions. For cars, the national average daily number of "hot soaks," defined as a period exceeding 1 hr when the vehicle's engine is not operating, ranges from 3.86 (weekend) to 5.38 (weekday), and averages 5.0. Trucks average 5.4 hot soaks per day.[43] Real world tests of recent (>1986) vehicles show that properly operating vehicles have hot soak emissions somewhat below 1 g/event for fuel-injected engines, and slightly above 1 g/event for carburetor-equipped engines.[44] Overall, emissions of 1 g/event appear representative, equivalent to one-half of the current hot soak/diurnal emission standard of 2 g. To arrive at the total evaporative emissions, 5 hot soaks per day, each equivalent to one-half the certified standard, plus 1 diurnal cycle are assumed. Together, the 5 hot soaks plus one diurnal cycle is equivalent to 3 hot soaks/diurnal losses per day, which is assumed in the following analysis. The resulting ratio of tailpipe and evaporative emissions is similar to that given by EPA's Mobile 5 model, which is based on historical data and average driving patterns. For example, Mobile 5 predicts that evaporative emissions constitute 61% of total in-use emissions for a Tier 1 gasoline car and 54% for a light duty truck.[22] The simplified approach gives 53% for a car and 47% for a LDT.

For a Tier 1 car, NMHC emissions total 0.53 g/mile. Tailpipe emissions are the largest contributor (47% of the total), followed by hot soak/diurnal losses (41%), running losses (10%), and refueling losses (2%).[45] The California evaporative standard (for ULEV, LEV II, and SULEV vehicles) reduces emissions in 2004 from 2 to 0.65 g/mile.[46] For ULEV and ULEV II vehicles, total NMHC emissions are

0.17 g/mile, and hot soak/diurnal emissions are the major contributor (42% of the total), followed by running losses (30%), tailpipe emissions (24%), and refueling (5%). For a Tier 1 heavy light duty truck (LDT4, MDV3) with a >30 gal fuel tank, the evaporative standard is 2.5 g. This vehicle sets the floor for NMHC emissions (0.73 g/mile) due to tailpipe emissions (0.39 g/mile or 53% of the total), hot soak/diurnal losses (38%), running losses (7%) and refueling losses (2% assuming 12 mpg).

The NMHC component score is based on the vehicle's total operating NMHC emissions and the following assumptions: fuel consumption as determined by vehicle fuel economy; the equivalent of 3 hot-soak/diurnal emission cycles per day; and hot soak, running, refueling and exhaust emissions as specified by the certification standard. The NMHC score is affected by fuel economy due to refueling losses, but the maximum effect is small (<0.4 point). Fig. 4 demonstrates the relationship between vehicle certification class and the NMHC score. The highest emitting vehicle (e.g., a 10 mpg Tier 1 LDT4) scores 0 points; a zero-emission-vehicle (ZEV) receives 12.5 points.

Particulate matter

PM emissions related to vehicles include combustion products forming $PM_{2.5}$ (particles $<2.5\ \mu m$ dia), larger PM from tire and brake wear, and PM from entrainment of dust on paved and unpaved roads. The form of ambient standards for PM has evolved to become more relevant to human health. The older standard controlling "total suspended particulates" (TSP) was replaced in 1986 by PM_{10} (particles $<10\ \mu m$ dia) which in turn was replaced in 1997 by $PM_{2.5}$. Current regulatory and health concerns emphasize tailpipe emissions. Unfortunately, $PM_{2.5}$ emission data are incomplete and no LCA inventory is available. TSP emissions for the vehicle life cycle have been quantified,[32] but there is no direct correlation to $PM_{2.5}$.

PM emissions from diesel-powered vehicles are controlled on a mass basis by US EPA and California regulations at 0.08 g/mile for light duty Tier 1 vehicles, 0.04 g/mile for TLEV, 0.01 g/mile for LEV, ULEV, LEV II, and SULEV, and 0 g/mile for ZEV. EPA does not specify standards for heavy light duty trucks (LDT3, LDT4), although California does as Tier 0 for MDV2 and MDV3 (0.08 g/mile). PM emissions from gasoline-powered vehicles are uncontrolled, although they are not necessarily innocuous. PM emissions from a properly operating gasoline-powered vehicle are likely to be on the order of 0.01 g/mile. Actual levels will be a function of fuel composition (sulfur, lead, etc.), engine load, and other factors. Like scores for the other regulated pollutants, the PM component score is based on certification levels and ranges from 0 to 12.5 points, as shown in Fig. 5. In the absence of vehicle-specific

information, gasoline-powered vehicles are assumed to emit 0.01 g/mile, providing a score (10.9 points) that is equivalent to a ULEV but slightly lower than a ZEV (12.5 points).

Carbon monoxide

Carbon monoxide (CO) is a local-scale pollutant emitted from the tailpipe. In-use emissions account for almost all CO emissions (Fig. 1). Scoring of CO follows the system described earlier, i.e., a Tier 1 medium duty truck, the highest emitter (5 g/mile), receives 0 points, while a ZEV receives 12.5 points (Fig. 6). Intermediate certifications exist for LDT (4.4 g/mile), Tier 1 cars, TLEV and LEV (3.4 g/mile), ULEV and LEV II (1.7 g/mile), and SULEV (1 g/mile).

Overall air pollution score

The suggested measure gives air pollutants a total of 90 points (40 for GHG emissions, 25 for O_3-forming pollutants NO_x and NMHC, and 12.5 each for PM and CO). For each pollutant, the score is proportional to the emission reduction from the baseline level, i.e., halving the emission doubles the score. The scoring of GHG emissions is not exactly proportional since the range does not extend to zero emissions, a minor adjustment made to maintain the desired weighting.

Scores for existing certification standards, summarized in Fig. 7, show relatively rapid increases as certification levels increase up to LEV or ULEV. Increases diminish at higher certifications (LEV II, SULEV), reflecting smaller emission reductions since most emissions have been eliminated. Gasoline and diesel scores are the same for LEV and above certifications. For gasoline-powered vehicles, the largest (7 – 8) point increases occur from LDTV4 to LDT2/LDT3, and from LDT2/3 to LDV Tier 1, i.e., from truck to car classifications, and from LEV to ULEV. Similar increases occur for diesel-powered vehicles for the first 6 steps, up to ULEV.

The total emission score, including criteria and GHG pollutants, is depicted in Fig. 8. As shown earlier (Fig. 2), fuel economy below 20 to 25 mpg is heavily penalized. Above 30 to 40 mpg, emissions must be decreased to significantly improve the score. The tradeoffs between vehicle efficiency and emission standards can be used by a consumer or manufacturer to achieve a certain environmental performance target. For example, a 20 mpg Tier 1 gasoline car can gain a maximum of 24 points by reducing emissions (to ZEV), or a maximum of 15.8 points by improving fuel efficiency (to 65 mpg). A combination of efficiency and emission control will yield the largest improvement that is practical for a given application.

Certification of vehicle emissions to levels other than those currently specified can be easily

accommodated. Scoring would follow the linear relationship between baseline levels and zero emissions. The need for representative and quality-assured measurements is critical, thus the proposed measure uses "official" certification standards. Other emission levels could be used given appropriate and equivalent quality-assurance. Also, as standards become more stringent (phase-out of Tier 1 standards by 2004 is anticipated), the floor will shift and recalibration will be necessary.

Electric and advanced technology vehicles

While most emissions during the operating stage may be eliminated, alternative technology vehicles (battery-powered, fuel cells, LPG, ethanol, methanol, etc.) involve "upstream" emissions in the fuel cycle that must be considered. The air pollution scores for these vehicles are derived in a manner consistent with conventional vehicles. For example, the DOE/EPA fuel economy of (battery-powered) EVs may be converted to gasoline energy equivalents (33.44 kWh = 1 gal gasoline)[47] and emissions based on national average emission factors for CO_2, CH_4 and N_2O.[22] GHG emissions are estimated using the vehicle fuel economy and near-term emission factors. Emission scores for alternative fuel vehicles require adjustments to be consistent with scores for conventional vehicles, which are based on certifications that consider only a fraction of current use-phase emissions. For conventional vehicles, omitted upstream emissions (from extraction, refining, and distribution) represent 41.9% of NO_x, 31.7% of NMHC, 2.5% of CO and 36.5% of PM of total emissions in the overall fuel cycle/vehicle use phases.[22] To allow comparisons to conventional vehicles, fuel cycle emissions for alternative fuel vehicles are lowered by the same percentages. As more alternative fuel vehicles make their debut, it may be preferable to increase the emission estimates for conventional vehicles to account for fuel cycle emissions. Both approaches are consistent and reward low emitting vehicles and fuel cycles.

Due to upstream emissions, a ZEV does not necessarily obtain the maximum possible air pollution score. Its score will depend on the vehicle efficiency and the energy infrastructure. As an example, a current EV obtains an emission score of 68.4 (component scores for GHG=31.8, NMHC=12.1, CO=12.2, NO_x=7.4, PM=4.9 using efficiency and emission data from Wang[22]). For comparison, a conventional Tier 1 car obtaining 22.4 mpg will obtain a emission score of 53.0 (component score points for GHG=26.7, NMHC=3.5, CO=4.0, NO_x=8, PM=10.9. Although the EV has higher NO_x emissions, GHGs, NMHC and CO emissions are considerably lower. The EV score is tied by a 44 mpg LEV, a 26 mpg ULEV, or a 21 mpg SULEV. These scores omit the solid waste and resource consumption components, described later.

The evaluation of electric and advanced technology vehicles is complicated by differences in the spatial pattern of emissions. These differences primarily affect impacts of the criteria and toxic pollutants as GHGs have a long residence time and are widely dispersed. For example, most electricity in the US is generated at several hundred power plants burning fossil fuels, most of which are equipped with tall smoke stacks and located in rural areas. Given the dilution and distance from population centers, health impacts for a given emission of CO, NMHC and NO_x (direct toxicity only) from power plants may be lower than the same emission in an urban area. Consequently, in their analysis DeCicco and Thomas[4,7] reduced the impacts from power plant emissions by 10-fold, and from refineries and factories by 5-fold. However, power plant emissions of NO_x and PM are regional pollutants, staying airborne for several days, and power plant NO_x is an effective O_3 precursor. Thus, no such adjustment was used here. Additional spatial factors include differences in the distribution of energy sources, e.g., more of the electricity in the Pacific northwest is generated by hydropower, and regional variation in ecological sensitivity, e.g., acidification most strongly affects poorly buffered soils and lakes like those in the Adirondack region of New York.

In addition to spatial factors, the composition of emissions in the fuel cycle of advanced technology vehicles may differ from emissions of conventional vehicles. As examples, coal-fired electric generating plants release large quantities of SO_2 and mercury (but relatively low emissions of NMHCs), and life cycle emissions of Pb for battery-powered ZEVs exceed those for conventional vehicles (using lead-free fuel).

Spatial and compositional differences in the vehicle use and fuel cycles also can influence environmental and health impacts attributable to both conventional and advanced technology vehicles. For example, a gasoline-powered vehicle in Texas contributes more to O_3 formation and impacts than the same vehicle in Nebraska. A SULEV vehicle in California using low sulfur fuel emits less PM than in areas where this fuel is unavailable. Differences in driving cycles, temperatures and other factors affect emissions. LCA inventories and impact assessments do not provide the data needed to address these issues. Additionally, the knowledge base needed for appropriate analyses has many gaps. Thus, the suggested indicator is currently limited to consideration of NO_x, NMHC, CO, PM and GHG emissions using national average emission factors. Conventional and advanced technology vehicles are treated consistently since the same pollutants and scaling are used. When quality-assured information becomes available, additional pollutants and regional considerations might be added to the metric.

Solid waste and resource consumption

Solid wastes are produced throughout a vehicle's life cycle, including materials production, assembly, operation, service and end-of-life phases. Waste generation and disposal consumes landfill space, potentially contaminates surface and groundwater, and has other impacts. Many impacts tend to be localized and difficult to assess without site-specific analyses. Waste generation without recycling also represents resource consumption.

Materials production, e.g., mining, is responsible for the bulk (60%) of wastes throughout the vehicle life cycle.[16] Most of these wastes are not considered solid or industrial wastes. Materials production and manufacturing together produce about 19% of the wastes in the vehicle life cycle.[16] Vehicle operation and service produce liquid wastes, e.g., brake fluid, engine coolant, engine oil, transaxle fluid, and windshield cleaner fluids, as well as solid wastes, e.g., air filters, batteries, brake pads, drive belts, lamp bulbs, exhaust systems, oil filters, PCV-valves, shock absorbers, spark plugs, tires, transaxle fluid filters, windshields, windshield wiper blades, etc. On a mass basis, these represent an estimated 10% of the total solid and industrial waste.[16] Vehicle end-of-life management, which includes dismantling, recycling, shredding and landfilling, has received considerable attention, and 70 - 80% of vehicle mass (mainly ferrous and non-ferrous metals) is currently recycled.[48,54] In comparison to the remainder of the life cycle, GHG emissions (CO_2 and CH_4) and energy consumption from end-of-life management are small, well below 1% of the total.[16,49] However, vehicle end-of-life is responsible for most (71%[16]) of the solid and industrial wastes.

Several indicators can be formulated to capture waste generation and resource conservation impacts at the production phase, end-of-life phase, or possibly both (as long as there is no double counting). For example, at the production phase, the recycled content measured as the percentage of weight of the total vehicle reflects the manufacturer's current efforts to conserve and recycle materials. Similarly, the non-recycled weight of the vehicle might be used to indicate resource consumption. Compared to the recycled percentage, the non-recycled weight provides an absolute impact measure that is proportional to resource consumption. This potential advantage is offset, however, by scaling issues resulting from the wide range of vehicle weights. For example, assume a 10 point scale where 0 represents only recycled materials and 10 represents the use of only virgin materials for the heaviest (8,500 lb) vehicle. Without any recycling, a 1,500 lb vehicle would score 8.2 (10 * [1 – 1500/8500]) points. To obtain the same score, 82% recycled content is required for the heavy vehicle. Thus, this measure de-emphasizes the importance of recycling efforts for smaller vehicles. As a second example, the percentage of material by weight that goes to landfill has been suggested as an environmental performance measure.[27] This end-of-life measure does

reflect waste reduction initiatives and increased recycling. However, the waste disposal fraction depends on economics and the technical infrastructure in the recycling industry, which is largely separate from vehicle manufacturing in the US. In addition, recycling/landfilling of vehicles occurs many years after manufacturing, during which the economics and technology may change significantly. Lastly, data regarding the vehicle weight fraction going to landfill for specific vehicle models are unavailable.

The suggested solid waste and material consumption component uses the recycled content of the vehicle, and is scored as 10 for a vehicle that uses 100% recycled content (by weight) and as 0 for a vehicle that uses no recycled materials. The small weight (10%) of the solid waste and material consumption score reflects the relatively minor contribution of the materials production, manufacturing and end-of-life phases to the vehicle's total environmental impact.

Unlike the other components of the performance measure, solid waste and material consumption data have not been published. The determination of recycled content must be done in a quality-assured manner, e.g., using a certified audit. For conventional vehicles, most weight is attributable to a small number of materials, e.g., ferrous metals (64%), plastics (9.3%), nonferrous metals (largely aluminum, copper and lead totaling 9%), rubber (6.9%), glass (2.8%), and fluids other than gasoline (2.7%).[16] Given that most weight is contributed by relatively few items, the determination of the recycled content of the bulk of a vehicle's weight does not pose significant practical difficulties.

Discussion and Conclusion

The suggested performance measure is designed to capture the major environmental burdens of vehicles on a brand/model basis. In the US, purchasers select among over 200 brand/models in 1,450 engine/drive train configurations. Configurations within a brand/model can be evaluated separately, or combined to develop a composite rating for that brand/model. Model-specific information is valuable to consumers contemplating purchasing decisions as well as manufacturers, "upstream" suppliers and the "downstream" waste and recycling industry, all endeavoring to improve the vehicle's life cycle performance. Such information supplements the incomplete and fragmented approaches represented by the current federal fuel economy ratings printed on new vehicle stickers, and the emission standard labeling programs of a few states.[7] The suggested performance measure can be used to compare models within a given year. Year-to-year comparisons may not be appropriate since the measure is calibrated to a particular year. Of course, purchasing decisions depend on many factors, for example, performance, body style, safety and environmental performance. The environmental performance measure may be most relevant to decisions among comparable vehicles, e.g., compact cars that have similar non-environmental

attributes.

Limitations

No single metric can capture the diversity of all possible impacts, concerns and trade-offs resulting from vehicles or other complex systems. While we believe that the suggested performance measure is justifiable, the weights combining the component scores are acknowledged to be judgmental and thus subjective. As discussed below, the quantification of the weights – as well as the formulation of any scalar or multidimensional performance measure – is restricted to the information that is currently available. However, this does not mean that such metrics should not be used. Rather, indicators are formulated to convey what is believed to be the most relevant information distilled into an easily understood scale.

The proposed metric has several limitations. It focuses on the use stage and does not consider all impacts from upstream discharges, e.g., manufacturing, fuel refining, and extraction and production of fuel and other materials that produce drilling and mining wastes, brines and other wastes. However, current LCA studies indicate that the environmental burdens of vehicles, like dishwashers, refrigerators, televisions, and similar goods,[7] arise largely from use. Several potentially important impact categories are either excluded or not well addressed, in particular ecological impacts, e.g., water pollution such as spills of MTBE-containing gasoline, acidification, and toxicity. Unfortunately, the available data and methodologies do not support an inventory, allocation and impact evaluation method that can provide quality-assured estimates of these impacts. To an extent, this issue is offset by the fact that all car manufacturers utilize identical or similar commodities, e.g., iron, steel, plastic, glass, electricity, etc., and all must comply with the same federal environmental laws. Thus, there is little reason to expect major differences among impacts for a particular material used in different vehicles.

The emission scores do not account for the unanticipated in-use deterioration of control systems, and the energy efficiency and GHG emission scores do not account for changes in fuel economy and the fuel cycle over the vehicle lifetime. With vehicle aging and deterioration, emissions may substantially increase. The proposed performance measure could be altered to incorporate anticipated changes, however, the proposed approach was selected for several reasons. First, measurements of in-use emissions can not be obtained until 3 or 4 years following model introduction, thus this information would not be timely for purchasers of new vehicles. Second, even after the application of deterioration factors to account for model aging, the relative differences between certification standards would be maintained, and scoring would be unaltered. Third, certification standards specify that emission controls must last a

substantial period, e.g., 5 years/50,000 miles, and the newest regulations specify a 100,000 to 150,000 mile lifetime. Fourth, component scores must be based on reliable information. The magnitude and apportionment of emissions due to system deterioration are uncertain. Similarly, predictions of the energy mix have not proven accurate. Overall, vehicle certification standards and fuel cycle information represent the highest quality data currently available.

In the future, manufacturing emissions may become more important as in-use emissions are reduced. For example, NMHC emissions from manufacturing are estimated to range from 5 to 20 kg/car.[15,32] In use, a Tier 1 car emits 72 kg of NMHCs; this will be reduced to 23 kg for a 2004 ULEV California vehicle. Both estimates assume emissions at certification levels. Thus, poorly controlled manufacturing emissions may approach or exceed ULEV operating emissions. At the same time, evolving "low-emission" manufacturing processes and more stringent pollution controls may decrease emissions. Certain manufacturing emissions may be reliably quantified and allocated to vehicle types, e.g., emissions from painting/coating. While currently unavailable, this information could be incorporated into the metric/. Future LCA inventories are expected to increase the scope and quality of upstream data. Inclusion of manufacturing emissions would provide a more complete assessment, although in-use and fuel cycle emissions are expected to continue to dominate life cycle emissions.

The environmental performance measure does not account for vehicle lifetime. A more durable and longer lasting vehicle may have a lower environmental impact, other things being equal, since manufacturing impacts are lower on a per mile basis. Recent trends do not support this assumption, however, since older vehicles can be large emitters. Also the metric does not account for vehicle comparability, i.e., an 8 passenger van is scored identically to a 2 passenger sports car. Impacts based on a passenger-mile or a ton-mile basis might be relevant in commercial applications, but a per mile basis appears the most relevant and compelling unit of analysis for personal vehicles.

Calibration and weighting

There are many issues involved in the formulation and calibration of indicators representing complex and diverse environmental impacts. While the proposed metric is believed to correlate to environmental impacts, it does not directly indicate impacts, and ultimately the weighting used in the indicator must be regarded as subjective. Different weights could be used to combine component measures related to emissions of air pollutants, recycled content, and other environmental factors. There is a large literature related to integrated assessments, risk-cost-benefit, damage functions and social costs, willingness-to-pay, and other evaluation techniques. With sufficient and accurate information, these techniques might

provide rational approaches for developing weightings among impact categories. However, their application to calculate health, environmental and natural resource impacts for the vehicle life cycle involves several challenging steps: (1) deriving appropriate emissions for all pollutants of concern; (2) quantifying source-receptor relationships, e.g., accounting for spatially and temporally varying environmental transport and fate processes; (3) defining and quantifying cause-effect relationships, e.g., dose-response curves for morbidity and mortality of humans and biota; and (4) providing consistent, representative and long-term valuations of impacts, e.g., determining the monetary equivalent of an acidified lake, extinction of a fish species, asthma attack, etc. To obtain meaningful weightings, quantifications throughout the four steps must be correct.

Several analyses have estimated social costs of some impacts from emissions in the transportation fuel cycle.[4,7,50,51] For example, the total health-related pollution impact for an average 1998 vehicle has been estimated as $0.0137/mile, with fractional contributions from NO_x (43% of the impact), SO_x (37%), PM_{10} (14%), NMHCs (4%), and CO (3%).[7] This analysis suggests that PM, NMHC and CO are relatively unimportant and should be de-emphasized. However, the damage function excludes many impacts, e.g., ecological impacts, and it does not fully represent variation and uncertainty. Consequently, impact estimates can vary over several orders of magnitude, e.g., the relative importance of PM has recently increased dramatically.[4] In contrast, the suggested indicator is simple and robust, that is, insensitive to uncertain parameters. Differences between the suggested measure and those based on social costs may not be that large since emission certification standards address multiple pollutants simultaneously, e.g., moving from Tier I to LEV reduces 3 of 4 regulated pollutants. Finally, it should be noted that the suggested performance measure is formulated primarily to guide purchasing decisions among the many brand/models available, not to determine regulatory decisions or research priorities. Such decisions require more comprehensive and sophisticated analyses than can be represented in any scalar metric.

There is some overlap between several of the component scores. The energy conservation score indirectly indicates resource consumption since vehicles with poor fuel economy tend to be heavy. The energy conservation score also affects the NMHC score, although the effect is small. These interactions and the other trade-offs (Figs. 7 and 8) should be recognized by manufacturers aiming to improve the environmental performance of their vehicles.

The suggested environmental performance measure is calibrated to the current vehicle mix and fuel cycle, in particular, the lowest and highest performing vehicles. As vehicle performance is upgraded, the

baseline will shift and scores across model years may not be comparable. The measure is primarily intended to enable comparisons among vehicles in a given model year.

Future work

This evaluation represents a "snapshot" of present-day conditions, using available data and analyses based on existing technology and market conditions. In the future, a number of factors are expected to change. As examples, widespread adoption of alternative fuels such as ethanol (corn, cellulosic) may decrease CO_2 emissions by 30 – 60%[52] or in the long term by up to 100%[53] compared to gasoline (although NO_x and some other emissions may increase). The recycled fraction of vehicles may change as vehicle composition is altered and plastic recycling efficiency is increased; also, landfill limitations or regulations may affect recycling and disposal practices.[54] Databases and data quality will improve in the future as LCA applications become more widespread and refined. Generic data quality concerns, especially for the inventory phase, include coverage, precision, completeness, representativeness, consistency, reproducibility and allocation. Particular needs include better data regarding PM and NMHC emissions, and manufacturing emissions (including toxic and persistent pollutants) on a model basis. With improved data, a meaningful allocation of manufacturing emissions to specific vehicle models may become feasible. The need to update the metric as additional information becomes available is strongly emphasized. These and other changes will result in better information regarding the life cycle impact of vehicles that can be incorporated into the suggested environmental performance measure.

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Figure legends

Fig. 1. Apportionment of air pollution emissions over the vehicle life cycle. Derived from [15, 16, 17].

Fig. 2. Scoring of energy efficiency/GHG emission score. Calibration based on model year 2000 vehicles obtaining 9.7 to 64.7 mpg.

Fig. 3. Relationship between vehicle certification standard, NO_x emissions, and the NO_x component score. Not all truck certifications are shown. The ZEV would only receive the full score with zero emissions throughout the fuel cycle.

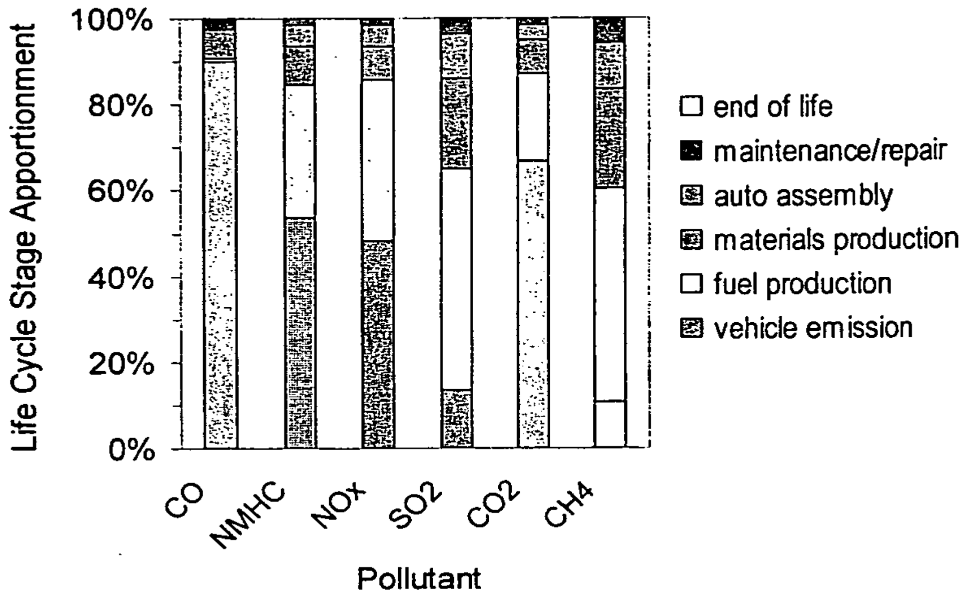
Fig. 4. Relationship between vehicle certification standard, total lifetime NMHC emissions, and the NMHC component score. NMHC emissions included tailpipe, evaporative, running and refueling. Results will shift slightly depending on vehicle efficiency. Not all truck certification classes are shown. The ZEV would only receive the full score with zero emissions throughout the fuel cycle.

Fig. 5. Relationship between vehicle certification standard, PM emissions, and the PM component score for diesel vehicles. Not all truck certifications are shown. The ZEV would only receive the full score with zero emissions throughout the fuel cycle.

Fig. 6. Relationship between vehicle certification standard, CO emissions, and the CO component score. Not all truck certifications are shown. The ZEV would only receive the full score with zero emissions throughout the fuel cycle.

Fig. 7. Points awarded for different certification standards for gasoline, diesel and zero emission vehicles. Based on certification standards for NO_x, NMHC, PM and CO. (Component scores for GHG emissions and recycled content must be added to obtain the full performance measure.)

Fig. 8. Total emission score based on vehicle fuel economy and emission certification standards. Not all certifications are shown. ZEV represents a battery-powered vehicle. Diesel- and gasoline-powered vehicle scores are identical for LEV and above certifications. The ZEV would only receive the score shown with zero emissions throughout the fuel cycle.



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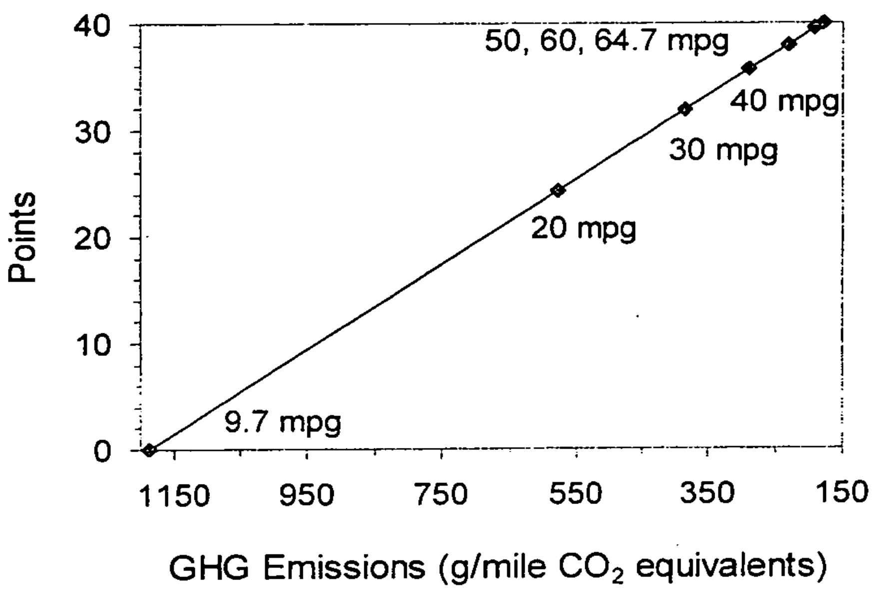

Fig. 2. Scoring of energy efficiency/GHG emission score. Calibration based on model year 2000 vehicles obtaining 9.7 to 64.7 mpg.

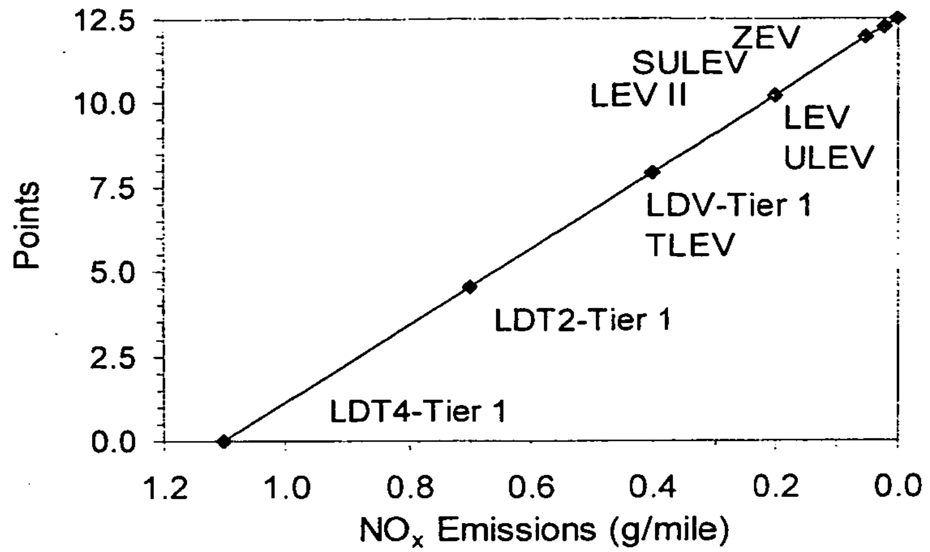

Fig. 3. Relationship between vehicle certification standard, NO_x emissions, and the NO_x component score. The ZEV would only receive the full score with zero emissions throughout the fuel cycle. Not all truck certifications are shown.

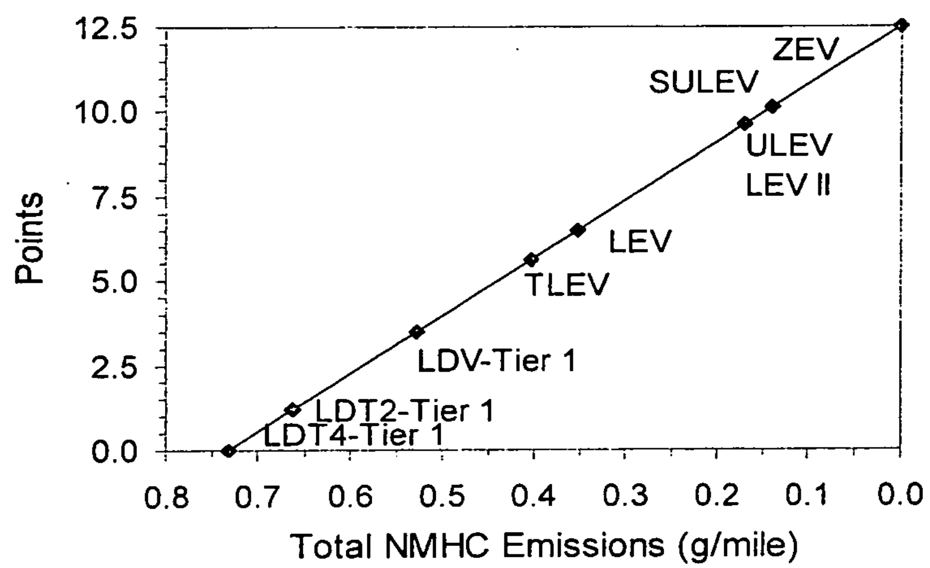

Fig. 4. Relationship between vehicle certification standard, total lifetime NMHC emissions, and the NMHC component score. Results will shift slightly depending on vehicle efficiency. The ZEV would only receive the full score with zero emissions throughout the fuel cycle. Not all truck certification classes are shown.

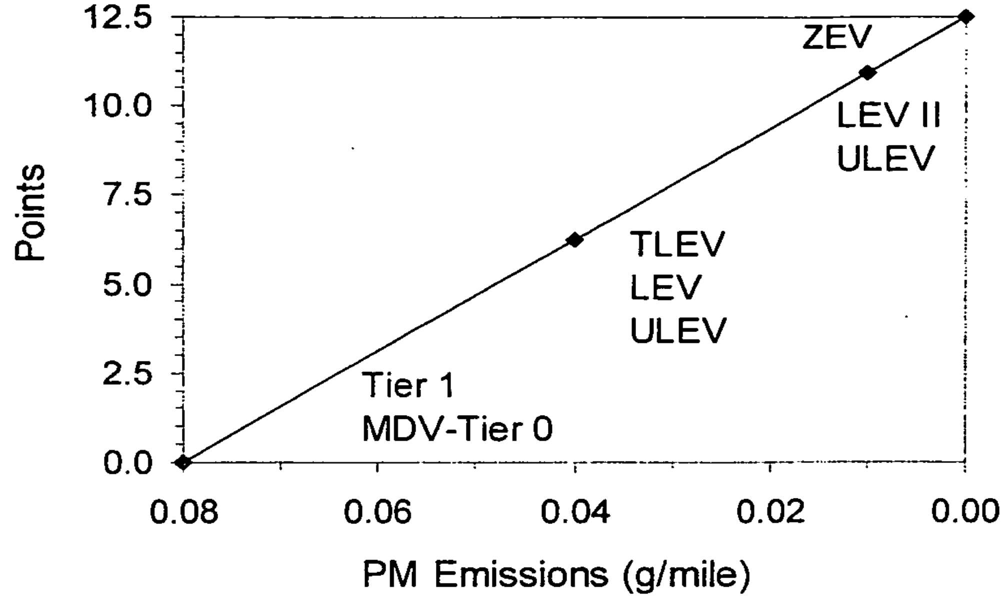

Fig. 5. Relationship between vehicle certification standard, PM emissions, and the PM component score. For diesel vehicles, PM emissions range from 0.08 to 0.01 g/mile, depending on certification. For gasoline vehicles, the PM emission rate is estimated as 0.01 g/mile, thus LEV II/ULEV scores apply. The ZEV would only receive the full score with zero emissions throughout the fuel cycle. Not all truck certifications are shown.

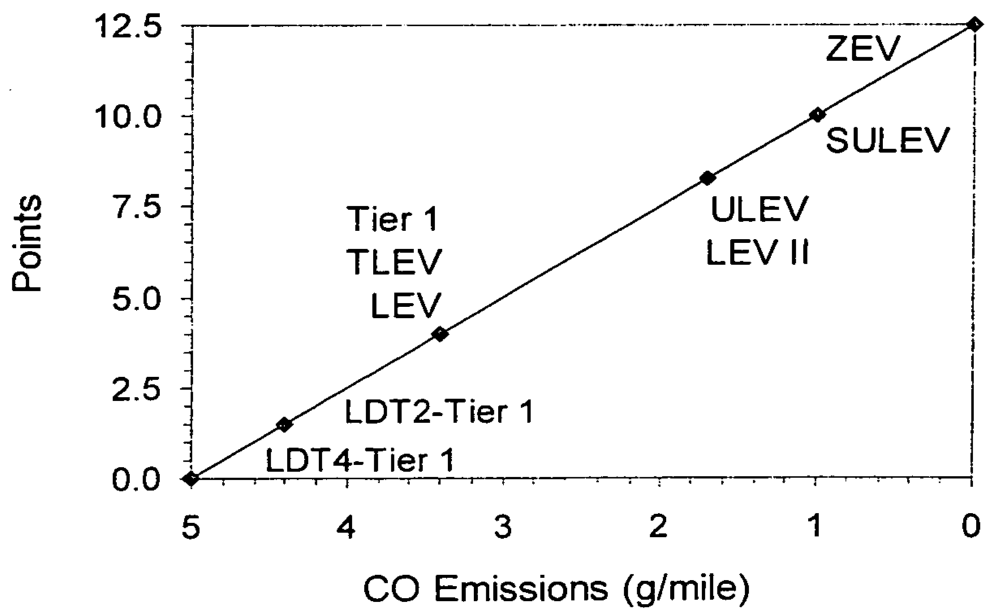

Fig. 6. Relationship between vehicle certification standard, CO emissions, and the CO component score. The ZEV would only receive the full score with zero emissions throughout the fuel cycle. Not all truck certifications are shown.

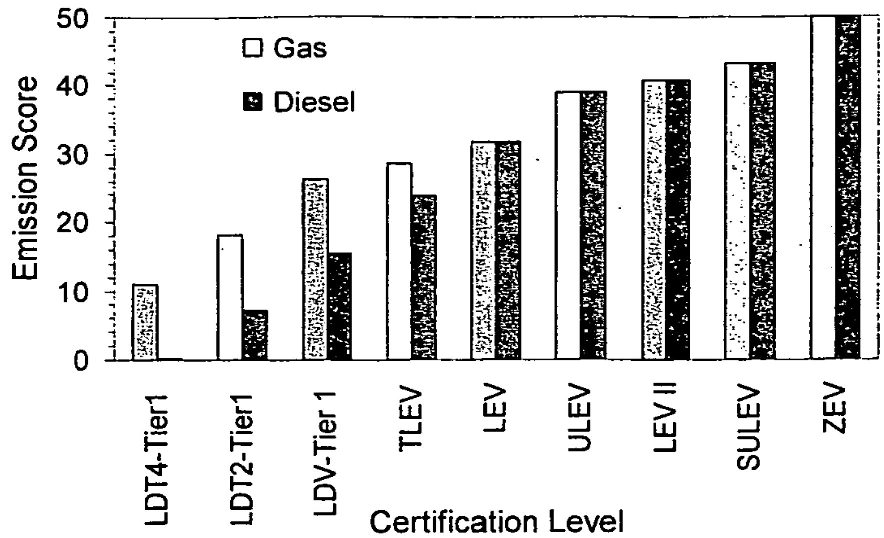

Fig. 7. Points awarded for different certification standards for gasoline, diesel, and zero emission vehicles. Based on certification standards for NO_x, NMHC, PM and CO. (Component scores for GHG emissions and recycled content must be added to obtain the full performance measure.) The ZEV would only receive the full score with zero emissions throughout the fuel cycle.

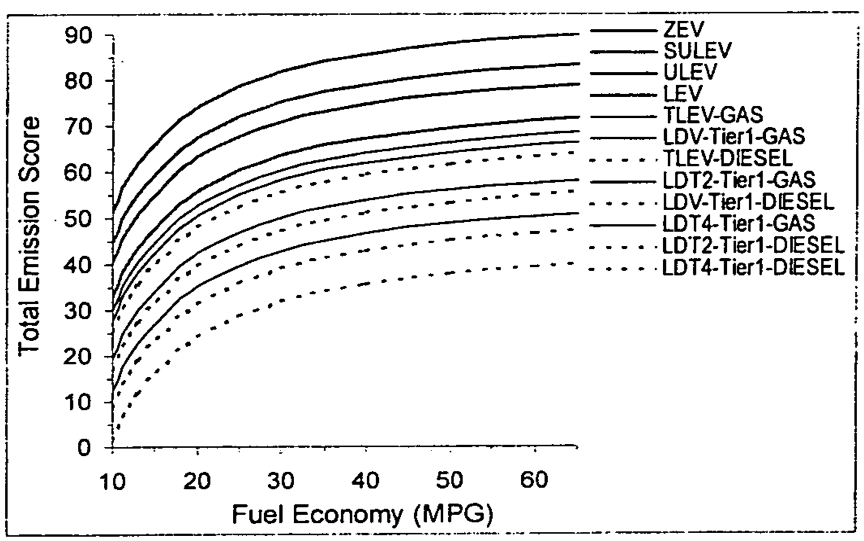

Fig. 8. Total emission score based on vehicle fuel economy and emission certification standards. ZEV represents a hypothetical vehicle with GHG emissions equal to a conventional battery-powered vehicle, but without NO_x, NMHC, PM and CO emissions. Diesel- and gasoline-powered vehicle scores are identical for LEV and above certifications. Not all certifications are shown. The ZEV would only receive the score shown with zero emissions throughout the fuel cycle.

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